# Size selectivity and escape mortality of gadoid fish in the Barents Sea trawl fishery

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# Summary

Responsible fisheries management involve, among other things, operations to avoid catches of juvenile fish. Technical measures of fishing gears to exclude small fish are thus generally regulated. Knowledge and control over the size selection characteristics of the fishing gear are therefore required, and the escaping fish should survive for the size selection to be a meaningful action. This thesis consists of four papers that deal with size selectivity and escape mortality of cod (Gadus morhua), haddock (Melanogrammus aeglefinus) and saithe (Pollachius virens) in the Barents Sea bottom trawl fisheries.

Our studies show that the trawl ground gears contribute to the overall size selectivity of bottom trawls. Netting bags were rigged underneath a commercial trawl with a rockhopper gear, along the fishing line, to collect fish that passed beneath the trawl. Approximately one third of the cod, a quarter of the haddock and seven percent of saithe available to the trawl escaped below the fishing line. Cod escape rates were highly length dependent with an estimated length at 50% retention ($L_{50}$) of 38.5 cm and selection range ($L_{75} - L_{25} = SR$) of 34.1 cm. Length dependence was less pronounced for haddock, and the escape rate of saithe was not length dependent. Some of the fish had been overrun by the gear as evidenced by scale abrasions and video observations.

The size selection of a bottom trawl for cod with the mandatory configuration of a sorting grid with 55 mm bar spacings and a 135 mm diamond mesh codend was compared to that of conventional codends of 135 and 155 mm mesh sizes. Previous indirect comparisons have indicated sharper selection (narrower $SR$) for sorting grids than conventional codends. Based on these comparisons, the use of grids was made mandatory in the Barents Sea bottom trawl fishery for cod. Our experimental studies demonstrated no evidence that the grid and mesh combination has sharper selection than conventional codends. The introduction of the grid corresponded to approx. 20 mm increase in mesh size, from 135 mm to 155 mm. The $L_{50}$ for the grid declined with increasing catch rates, but grid selection appeared less affected by seasonal variations in girth and fish condition than mesh selectivity.

Mortality of cod, saithe and haddock that escaped through meshes and sorting grids were studied in four field experiments. Cod and saithe mortality were negligible, suggesting that selection devices serve their purpose as conservation tools regarding these species. Haddock mortality was higher and inversely related to fish length. Their mortality could neither been shown to depend upon selection device nor fishing intensity. There was, however, a considerable variation between replicates masking any such possible effects. It is concluded that the trawl passage, but not mesh and grid penetration is the

primary cause of mortality. Injury analysis supports this suggestion. The mortality estimates were confounded by methodological problems. Potential sources of experimentally induced mortality were identified throughout the experiments and the methods subsequently improved. The confounding methodological effects are accounted for in a model describing haddock escape mortality.

# Útdráttur

Ábyrg fiskveiðistjórnun felur m.a. í sér aðgerðir til að komast hjá veiðum á ungviði fiska. Útbúnaður veiðarfæra til að skilja út smáfisk er því jafnan lögboðinn sem aftur krefst þekkingar og stjórnar á því hvernig veiðarfæri halda smáfiski (kjörhæfni). Markmiðum með kjörhæfni veiðarfæra verður einungis náð ef fiskar sem sleppa lifa. Þessi ritgerð samanstendur af fjórum greinum um kjörhæfni og lífslíkur þorsks (*Gadus morhua*), ýsu (*Melanogrammus aeglefinus*) og ufsa (*Pollachius virens*) sem sleppa frá botntrollum við fiskveiðar í Barentshafi.

Í þessari ritgerð er sýnt að fótreipi botntrolls hefur áhrif á heildarkjörhæfni veiðarfærisins. Netpokar voru festir undir fiskitroll með steinastiklu, meðfram fiskilínunni, til að safna fiski sem slapp undir trollið. Um það bil þriðjungur af þorski, fjórðungur af ýsu og sjö prósent af ufsa í trollopinu slapp undir trollið. Hlutfall þorsks sem slapp var háð fisklengd og lengd þar sem 50% veiðist ($L_{50}$) var 38.5 cm og kjörsvið ($L_{75} - L_{25} = SR$) 34.1 cm. Slíkt lengdarsamband var ekki jafn skýrt fyrir ýsu, og flótti ufsa undir trollið var óháð fisklengd. Hluti þeirra fiska sem sluppu báru þess merki að keyrt var yfir þá.

Kjörhæfni fiskitrolla m.t.t. þorsks með hina lögboðnu samsetningu af smáfiskaskilju með 55 mm rimlabili og trollpoka með 135 mm möskvastærð var borin saman við kjörhæfni hefðbundins poka með 155 mm möskvastærð. Niðurstöður úr fyrri óbeinum samanburði höfðu gefið til kynna að notkun skilju leiddi af sér skarpari kjörhæfni en með hefðbundnum trollpoka. Skiljunotkun var því lögboðin við botntrollsveiðar í Barentshafi. Í þessari ritgerð eru kynntar niðurstöður sem sýna m.a. að smáfiskaskilja leiðir ekki af sér greinanlegar betrumbætur hvað varðar skerpu í kjörhæfni samanborið við hefðbundinn trollpoka með 155 mm möskvastærð. Innleiðing smáfiskaskilju í reglugerðir samsvaraði því í raun aukningu í möskvastærð um 20 mm, frá 135 mm til 155 mm. $L_{50}$ fyrir skiljuna minnkaði með auknum afla, en svo virðist sem kjörhæfni skiljunnar sé minna háð umgjörð og ástandi fisks en kjörhæfni trollpoka.

Lífslíkur þorska, ufsa og ýsu sem sluppu gegnum möskva og smáfiskaskiljur voru rannsakaðar í fjórum vettvangsrannsóknum. Afföll þorska og ufsa voru óveruleg sem gefur til kynna að aðgerðir til að skilja út smáfiska þjóna tilgangi sínum hvað varðar þessar tegundir. Afföll ýsu voru hærri en minnkuðu með aukinni fisklengd. Hvorki var sýnt að kjörhæfnibúnaður né aukinn sóknarþungi á miðum hefðu áhrif á lífslíkur ýsu. Þess ber þó að geta að verulegur breytileiki var milli einstakra athugana sem yfirgnæfir hugsanlegan mun. Ferðalag ýsunnar gegnum trollið, en ekki möskva- eða rimlasmug er talið helsta dánarorsök. Staðsetning sára og hreisturtaps á fiskinum staðfestir þá niðurstöðu. Erfiðleikar við framkvæmd rannsókna eru taldir hafa aukið á afföll ýsunnar. Þróun aðferðafræði

er lýst, og mögulegir áhrifavaldar affalla vegna tæknilegra örðugleika voru greindir samhliða framkvæmd rannsóknanna og aðferðir bættar í framhaldi af því. Þættir sem höfðu áhrif á afföll voru teknir með í reiknilíkan sem lýsir lífslíkum ýsu eftir ferðalag gegnum troll.

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# 1 Introduction

The FAO code of conduct for responsible fisheries (FAO 1995) provides a framework for ensuring sustainable exploitation of aquatic living resources. The right to fish carries with it the obligation to do so in a responsible manner, and to ensure that appropriate research is conducted into all aspects of fisheries.

Trawling is one of the most widespread fishing methods in the world (Valdemarsen and Suuronen 1993) and has been used for centuries. A beam trawl known as *wondyrchoun* was described in the UK as early as 1376 (Robinson 1996). A two-boat trawl, *paranzella* gear was commonly used off the coasts of Italy, Holland, Spain and France prior to its introduction on the Pacific coast of the United States in 1876 (Scofield 1948). After the emergence of steam trawlers, the otter trawl was introduced into the British trawl fishery in 1895 by Mr. Scott of Granton (Robinson 1996).

A simplified approach is to consider trawl as a towed filtering device, in which the organisms that enter the gear are sieved by the meshes, primarily at the codend. The size-selection characteristics of the trawl can thus be controlled by altering the mesh size of the codend. After the introducton of trawls, regulations concerning minimum mesh size for young fish conservation were soon considered, and the first known mesh size regulations were introduced in the 16th century (Burd 1986). Minimum mesh size is now widely regulated for young fish protection. In the cod fisheries in the Norwegian Economic Zone in the Barents Sea, the codend mesh size has gradually been raised to 135 mm in the 1980s (Nakken 1994).

In order to protect immature fish, a sorting grid was made mandatory in the Barents Sea bottom trawl fishery in 1997 (Kvamme and Isaksen 2004). The grid was believed to provide better selectivity properties than the codend alone. That belief, however, was not well-founded.

Studies of survey trawls have shown that considerable numbers of fish escape underneath the trawl, and the ground gear appears to be size-selective for some species and situations (Engås and Godø 1989b; Walsh 1992; Dahm 2000). However, escapes of fish beneath commercial trawls have not yet been quantified.

Fish that escape but die as a consequence of contact with gear contribute to the overall mortality caused by fishing. In spite of the use of mesh-size regulations for juvenile conservation for several hundred years, attempts to investigate escape mortality were not made until the 1920s (Burd 1986, citing Davis 1934). Escape mortality is rarely known and therefore not included in fish stock assessments. Most types of fishing gear can injure fish that encounter the gear but escape, and are therefore a potential source of unaccounted mortality (Davis 2002). Mesh and/or grid penetration is one potential factor affecting survival of escaping fish and has been studied by several researchers. While species such as cod and saithe tolerate mesh penetration quite well, reliable mortality estimates for haddock have been difficult to obtain, as this species is more susceptible to experimental treatments (Soldal et al. 1993; Main and Sangster 1990).

## 1.1 Trawl selectivity

### 1.1.1 The concept of trawl selectivity

Information on how various types of fishing gear select fish of different species and sizes is important for fisheries management, and is the basis for technical regulations introduced to fulfil the terms of the relevant fishing management schemes.

For towed fishing gears, retention probability for a given mesh size and species is a function of fish size. The trawl is thus said to be size-selective. The main mesh selection is believed to occur through the codend meshes (Wileman et al. 1996), and most studies of trawl selection have therefore focused on the codend. Fish whose girth is less than the circumference of a mesh in the codend can pass the mesh and avoid capture, while fish with girth well above the mesh circumference are physically hindered from penetrating. Size selection, however, is generally described as a function of fish length, since length is easier to measure than girth. Although there is a linear relationship between girth and length, the relationship may vary with condition, season, and area (Wileman et al. 1996).

Millar and Fryer (1999) partitioned the selection process implicitly by giving three definitions of selection curves, each differing in the population being selected from.

The contact-selection curves, $r(l)$, describe selection from the population of fish that actually come into contact with the device. The available-selection curves, $a(l)$, describe selection from the fish that are available to, but may not contact a selection device. Finally, the population-selection curves $s(l)$ describe the probability that a fish from the population is captured. Estimates of $r(l)$ can be obtained when the proportion retained can be quantified, either directly by collecting escapees in a cover, or indirectly with the twin trawl method (Millar 1992). Meaningful estimates of $s(l)$ and $a(l)$ can only be obtained from $r(l)$ if independent knowledge of fish avoidance and the representativeness of the localized fish concentration is available (Millar and Fryer 1999). In addition, the concept of fleet selectivity (Fryer 1996) may be determined for a fleet structure, e.g. a gill net fleet, a trawler fleet, or even further sectioned by vessel size and gear type. The above definitions apply in general, not only for towed gears.

For codend selection, $r(l)$ is usually described by a sigmoid-shaped curve with asymptotes of 0 and 1 (Figure 1) and is generally described in terms of 50% retention length ($L_{50}$) and selection range ($SR$). $L_{50}$ is the length of fish whose retention probability is 0.5. $SR$ is the difference in length of fish (in cm) that have 0.25 and 0.75 retention probabilities, and is thus a measure of curve steepness - the lower the value, the sharper the selection.

Catch comparison trials measure only the differences in size composition of catches,

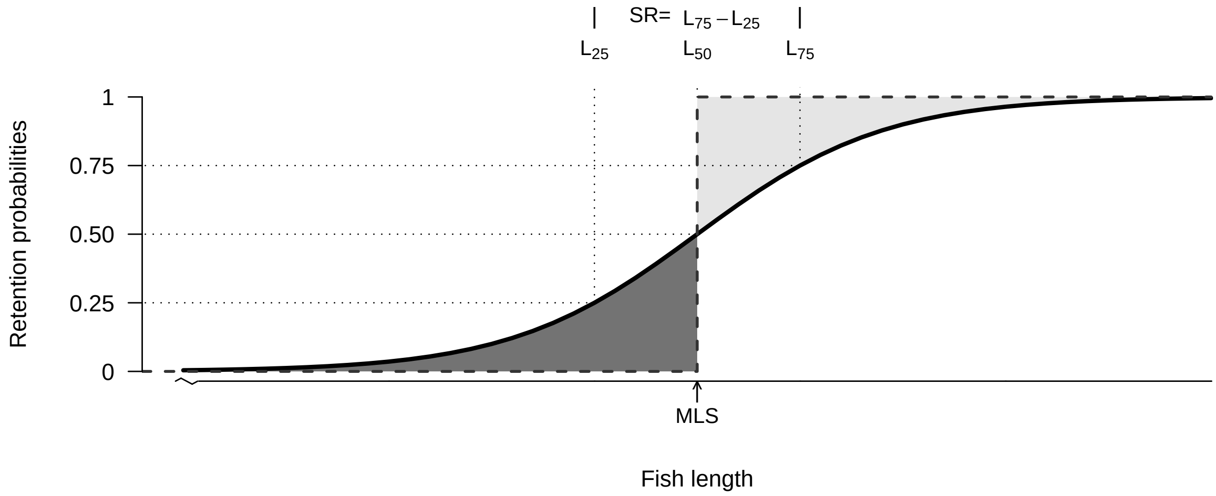


Figure 1: A sigmoid-shaped retention curve for towed fishing gear (bold curve). For selection other than 'knife edge' (dashed line, $L_{50}$ = MLS), a trade-off between undersized fish (dark grey field) and loss of marketable fish (light grey field) is entailed.

and the results therefore depend on the population being fished (Ferro and Stewart 1990). The selection curves, on the other hand, are a means of presenting the results independent of the population being fished.

### 1.1.2 The use of selectivity estimates and management objectives

Knowledge of size selection can be used in estimation of escape and discard mortality, yield-per-recruit analysis, age- and length-based population models, population length frequencies, length at age, etc. (Millar and Fryer 1999). Attempts to improve size selectivity are aimed at reducing discards while maintaining catches of marketable fish. Hence, improvements imply narrower $SR$, and the underlying assumption is that fish selected out during the capture process will survive. The majority of discarded gadoids are assumed to die (Carr et al. 1992; R. and Ross 1993). Discard rates have been estimated directly onboard fishing vessels (Hylen 1977; Tamsett et al. 1999) and indirectly by using other data sources and assumptions (e.g. Pálsson 2003; Dingsør 2001). Minimum legal size (MLS) is widely used to define a reference length below which fish should be neither caught nor landed. If $L_{50}$ is below MLS, discarding is induced but most of the marketable fish are retained, while by choosing an $L_{50}$ above MLS, discarding is reduced but at the cost of loss of marketable fish. Any form of the selection curve, other than knife-edge selection, i.e. $SR$=0 (see e.g. MacLennan 1995), will lead to some compromise between discarding (dark grey field on Figure 1), and loss of revenue (light grey field).

By reducing discards, more fish will enter the catchable stock, and in the long run, catches will increase, provided that fishing mortality is kept at a level at which the spawning stock is maintained within biologically acceptable levels (Armstrong et al. 1990). As an example, the yield of the North Sea haddock could be substantially improved if all discards could be avoided (Cook 2003), and the spawning stock could be almost doubled (Shepherd 1990). Therefore, saving the juveniles and harvesting moderately from the older part of the stock makes sense.

However, the economic benefits of sharp selection may not be as obvious. MacLennan (1995) argues that increasing the $SR$ could result in more stable yield provided that the fishing effort was adequately controlled. When Kvamme and Frøysa (2004) modelled the population selection, they showed that changing $L_{50}$ has a stronger effect on the long-term yield of the North East Atlantic (NEA) cod stock than changing $SR$. Furthermore, Kvamme (2005) showed in simulation studies that changes in $SR$ ($1 \leq SR \leq 15$ cm) had only minor effects on the mean annual catches and stock biomass of NEA cod compared to changes in $L_{50}$ ($45 \leq L_{50} \leq 80$ cm).

In summary, attempts to 'improve' selection by narrowing the selection range are made to fulfil regulation criteria set by fisheries managers. The benefits for the development of the fish stocks are less obvious.

### 1.1.3 Factors affecting selectivity

#### Controllable factors

The selection process begins onboard the fishing vessel, when the captain chooses the fishing ground. Vessel noise and sound produced by the warps affect swimming behaviour (Engås 1991; Handegard and Tjøstheim 2005) and may thus influence selectivity. Selection at seabed level continues when the fish are herded by the doors and sweeps towards the trawl opening. Different sweep angles result in differences in the size distribution of catches of some species (Engås and Godø 1989a; Somerton and Munro 2001). It is therefore tempting to believe that with respect to preferred size selectivity, an optimal sweep angle exists for each individual species.

The herded fish then approach the trawl mouth and some will enter. Studies of survey gear have shown significant size selection of the ground gear in some species (Engås and Godø 1989b; Walsh 1992). Of small cod and haddock (<20cm) in front of the trawl opening, 85-90% passed under the fishing line of the Norwegian survey trawl rigged with a roller gear (Engås and Godø 1989b). How to alter this selection process is not well understood. The weights and dimensions of and clearance between the discs/bobbins of the ground gear are presumably crucial factors. Moreover, different gear-types (e.g. roller gear, rockhopper gear) may perform differently. Vision is also likely to play a role in the selection process, which suggests that towing depth and contrast colours may influence escape rate.

After the fish enter the trawl opening, some selection may occur in the belly section, but it is usually assumed that most selection in a trawl takes place through the codend (Wileman et al. 1996).

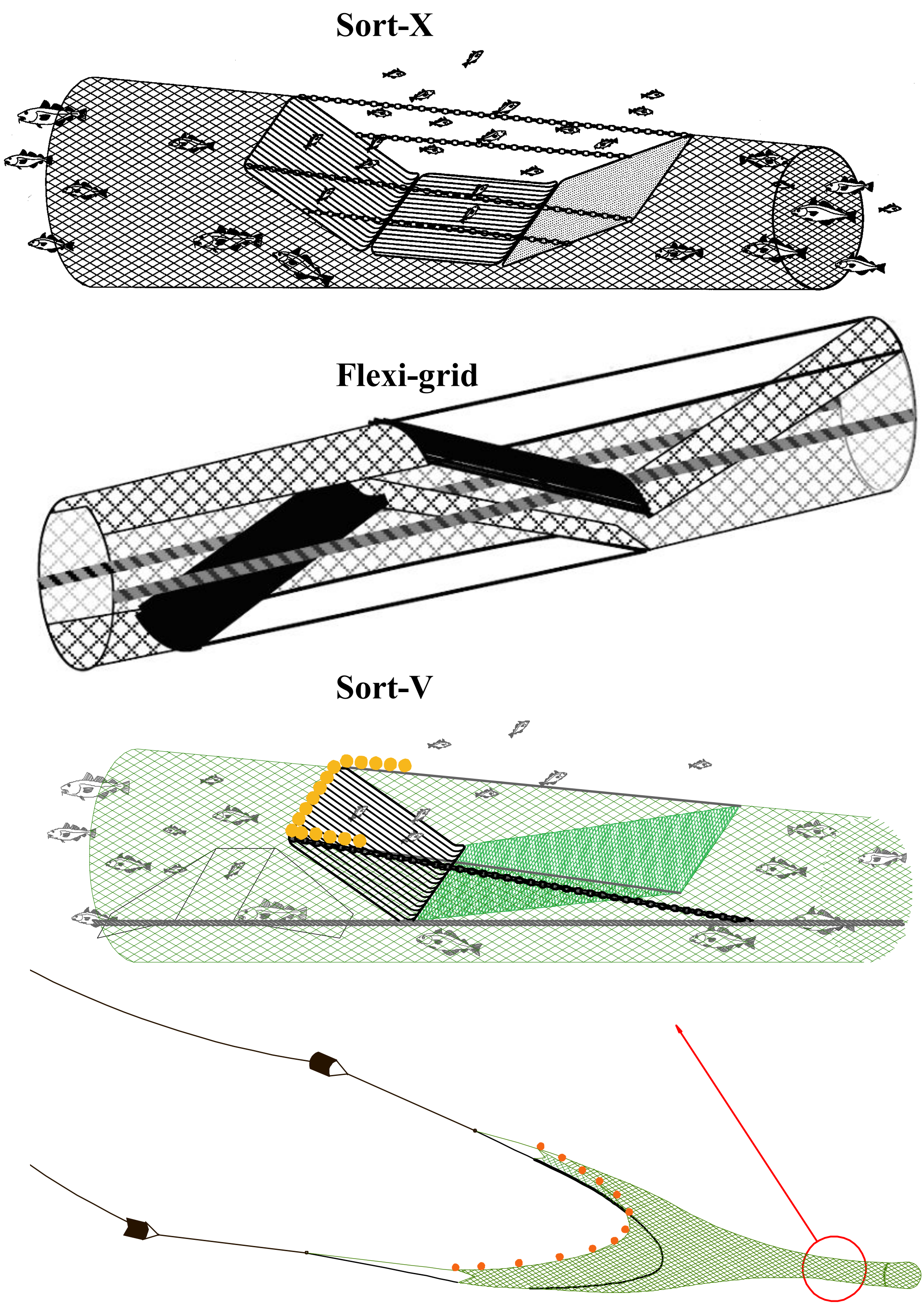


Figure 2: The three grid alternatives permitted in the Barents Sea demersal fisheries.

When fish accumulate in the end of a diamond mesh codend, it becomes bulbous and the codend meshes remain open only within a small area, directly in front of the bulge (Robertson 1988). By increasing the codend mesh size the $L_{50}$ increases (Reeves et al. 1992; Halliday et al. 1999). Keeping the codend meshes more open has also been shown to increase the $L_{50}$ for that particular mesh size. This can be achieved by inserting square mesh windows (Lowry et al. 1995; Madsen et al. 2002), constructing the whole codend as a square-mesh codend (Isaksen and Valdemarsen 1986; Cooper and Hickey 1988), by using short lastridge ropes (Isaksen and Valdemarsen 1990), or twisting the meshes in the codend 90° so that the side-knots point forward (Moderhak 2000). The $L_{50}$ of the codend can further be changed by altering the codend circumference, the length of the extension piece between the trawl-belly and the codend (Reeves et al. 1992), and codend-twine stiffness (Ferro and O'Neill 1994) and thickness (Lowry and Robertson 1996).

$SR$ has been found to increase with mesh size (Halliday et al. 1999; Madsen et al. 2002). A more general explanation is that $L_{50}$ and $SR$ are positively correlated (Madsen et al. 2002). This may apply irrespective of the selectivity device. Using square mesh codends (Halliday et al. 1999), and windows in the top panel of the codend (Madsen et al. 2002) narrower $SR$s were achieved than with diamond mesh codends for small catches of cod and haddock. To date, there is no firm evidence showing that either codend circumference, codend extension length, twine material or thickness affect $SR$ (Kynoch et al. 1999; Tokaç et al. 2004).

The use of selection grids has been mandatory in the Barents Sea trawl fisheries since 1997. Three grids are now accepted: Sort-X, Sort-V (the single grid) and the Flexi-grid (Figure 2). Most of the selection takes place through the grid, which is placed in front of the codend, while the codend performs a secondary selection process (Kvamme and Isaksen 2004). The selection grids were believed to give narrower $SR$ than traditional codends based on comparisons across surveys (Isaksen et al. 1990; Larsen and Isaksen 1993; ICES 1998). However, direct comparisons were not performed. In retrospect, no evidence has been provided to show that the selectivity properties of any of these grids are superior to traditional codend mesh selectivity.

### Uncontrollable factors

Different selectivity surveys may produce different results, due to a number of uncontrollable factors. Seasonal variations in girth, temperature and/or fish condition have been shown to affect the $L_{50}$ of haddock for diamond codend in the North Sea (Özbilgin et al. 1996) and cod in the Baltic Sea fisheries (Tschernij et al. 1996). The girth of a given length of fish varies throughout the year depending on the stage of gonad development and food availability, hence size selectivity would be expected to vary. However, the seasonal effects cannot be explained by variations in girth alone (Özbilgin et al. 1996).

Factors affecting swimming performance are also likely to affect mesh selection since mesh penetration requires swimming. The swimming performance of fish generally falls with decreasing temperature (He 1993; Moyle and Cech 2000). The swimming performance of cod depends on their condition (Martínez et al. 2003) and may also affect the probability of mesh penetration. Hence, variations in condition may affect codend selectivity.

Sea state (O'Neill et al. 2003), and thereby weather, vessel size, type of hauling method (stern trawler/side trawler) (Tschernij and Holst 1999) and possibly towing speed (Dahm et al. 2002) also affect mesh selectivity.

Several studies have demonstrated an increase in $L_{50}$ with catch size. Kvamme and Isaksen (2004) found a positive correlation of $L_{50}$ in cod with catch size for catches ranging from 1000 to 6500 kg. For catches up to 1100 kg, an $L_{50}$ of haddock for a diamond mesh codend (O'Neill and Kynoch 1996; Graham et al. 2004) and three out of six data sets for cod (Dahm et al. 2002) was also found to be positively correlated with catches. The codend diameter, and thus mesh opening and selectivity, increases with catch and probably stabilises when a point of maximum diameter is reached (O'Neill and Kynoch 1996).

Due to such uncontrollable factors, direct comparisons between selectivity measurements should be made as close in time and space as possible, and solely within the same trial.

### 1.1.4 Methodological considerations

#### Grid and codend selection

There are two main methods of estimating the selectivity of towed gears; the covered codend method and the twin trawl method (Wileman et al. 1996). The main advantage of the covered codend method is that the retention probabilities for each length class can be calculated directly, since the escaped fish are retained in the cover. However, the cover enclosing the codend or the grid may alter the water-flow around the codend and through the grid, and/or the grid angle, thus influencing the selection properties of the gear. The twin trawl method overcomes this problem, but the uncertainty related to estimating the selectivity of one codend by comparing it with another codend may lead to wider variations in selectivity estimates (Wileman et al. 1996; Madsen and Holst 2002). The comparison between the two methods by Madsen and Holst (2002) showed clearly that the variances obtained with the twin trawl method are significantly higher than those obtained with the covered codend method. Shephard (2000) found significant differences between the estimates obtained with the covered codend and the twin trawl method, while Madsen and Holst (2002) obtained a 15% lower (although not statistically significant) $SR$ using the covered codend method than with the twin trawl method. They obtained simultaneous estimates with the twin trawl and the covered codend method by using a cover surrounding one of the codends. In 13 of the 17 hauls, the $SR$ for the covered codend method was lower than for the twin trawl method. However, they did not detect a significant difference in $SR$, even though the probability of this outcome occurring by chance is negligible (Wilcoxon rank test, $p<0.05$).

### Ground gear selection

Some authors have observed fish passing beneath the fishing line of a trawl, drawing on observations by divers in shallow waters ($<$ 30 m) (Main and Sangster 1983) or by using cameras and artificial light (Glass and Wardle 1989). As Barents Sea demersal trawling mainly takes place at depths of 200-300 m, the ambient light level is presumably low and fish behaviour in the trawl opening when using artificial light may not reflect natural circumstances.

For quantitative measurements, all the fish that enter the trawl opening and pass beneath the fishing line must be retained. Engås and Godø (1989b) and Walsh (1992) used three collecting bags, one for the centre part of the ground gear and one for each wing part, while Munro and Somerton (1997) used one large bag covering the whole fishing line. The ground gear of the bags needs to be small, and because they are close to the bottom there is a risk of damaging the bags. The bottom therefore needs to be smooth, especially for the single-bag rig, as one large bag uses more netting than do three smaller ones. 'Abrasion-resistant' netting material should be chosen for the same reason.

The additional hydrodynamic drag induced by the bags may alter the geometry of the trawl, and thereby the trawl performance. Differences in wing spread and headline height, with and without the bags, can be used as an indicator of alterations in trawl geometry.

### Statistical analysis

In the analysis of covered codend data the logistic curve is predominantly used and belongs to the family of generalized linear models (McCullagh and Nelder 1989). Selection curves for the covered codend method can thus be fitted using most statistical software packages. Millar (1992) described how the selectivity parameters can be determined by means of indirect methods, i.e. the twin trawl method. The method allows a split parameter to be estimated, i.e. the two trawls do not necessarily have to have equal catch efficiency, but it is assumed that the size distribution of the fish that enter both nets is the same.

Variations in the selection process have two likely causes: controllable changes, and uncontrollable factors (see section 1.1.3). Fryer (1991) showed that these uncontrollable factors (between-haul variation) must be taken into account in order to avoid misleading selectivity estimates. If not, uncertainty in parameter estimates will be underestimated and spurious statistical inferences may be made. The model introduced by Fryer (1991) allows for testing of fixed variables such as different selectivity devices, taking the between-haul variation into account.

A fundamental question that must be addressed at the planning stage of a comparative experiment concerns the sample sizes needed to detect some pre-determined difference. The power of a test is the probability of detecting an existing difference, and it depends on four factors: (1) The variance of the response variable (2) the size of the difference in the response variable that we wish to detect as significant (3) the risk of Type I error (rejecting a true null hypothesis) and (4) the risk of Type II error (accepting a false hypothesis) (Crawley 2002).

The size of the difference one wishes to detect may be unknown. Moreover, the variance may not be known in advance. Some idea of the variance may then be obtained from the literature or previous experiments. Research that attempts to test for the effects of various treatments, without knowing their power before the experiment, can result in a low probability of detecting an existing effect (Peterman 1990). If a subsequent power analysis shows that a given experiment had low power, the experiment may have to be repeated. Unfortunately, most fisheries research papers in which $H_0$ is asserted to be true do not report power (Peterman 1990).

## 1.2 Escape mortality

### 1.2.1 Mortality estimates for stock assessment

Studies of escape mortality concern the fate of fish that encounter but then escape from fishing gears. Fish escape mortality is a waste of resources and causes uncertainty in stock assessment models.

In Virtual Population Analysis (VPA) models (e.g. Sparre 1991), the overall mortality rate $Z$ is split into fishing mortality, $F$, and natural mortality, $M$. Fishing mortality accounts for removal of fish by fishing, while natural mortality covers mortality resulting from a variety of causes, e.g. predation and disease. Fishing mortality can be split into subcomponents (ICES 2005b) such as landed and reported catch ($F_c$) and escape mortality ($F_e$). At present, escape mortality is not included in stock assessment models, as it is rarely known, but Breen and Cook (2002) have shown how escape mortality can be incorporated.

The escape mortality rate at stock level concerns the proportion of a stock that contacts fishing gear, is selected out and consequently dies. Mortality estimates of fish that have escaped from trawls are therefore of limited value without estimates of the number of fish that encounter trawls and of gear selectivity. Escape mortality also needs to be seen in relation to natural mortality, which can be high for juveniles that are more susceptible to capture by predators (Sogard 1997; ICES 2005a). Wileman et al. (1999) concluded that since the escape mortality of haddock west of Scotland was mostly limited to the 0-

group, which has high natural mortality, their observed escape mortality for that age-class (about 20%) would not significantly change the results of stock assessments. However, escape mortality should be avoided both for economic reasons, i.e. in order to maximise the long-term yield by removing only the fish that are of commercial value, and for moral reasons, i.e. that only what will be utilised should be killed.

### 1.2.2 Methodological development

Studies of escape mortality began in the early 20th century (Burd 1986, citing Davis 1934) and have looked at a number of species escaping through codend meshes and grids (e.g. Sangster et al. 1996; Soldal et al. 1993; Suuronen et al. 2005. When studies are performed in the laboratory, the researcher can isolate and test influential factors in a controlled experimental environment. Nevertheless, the whole fishing process cannot be simulated, and the results may not be directly relevant to commercial fishing conditions. Field studies have the drawback of having less control over factors (e.g. weather, temperature and currents), that have the potential to influence results. However, field studies are more similar to commercial conditions, although some modifications may be difficult to avoid; e.g. restrictions when choosing location and depth, research equipment attached to the gear and transfer of fish from the sampling location to an observation site.

Experiments carried out in the 1920s and 1930s, in which codend escapees were collected in small-meshed covers and brought on board, showed that small fish could escape apparently unharmed (Burd 1986, citing Davis 1934). Similar experiments in the 1950s confirmed these results for cod and haddock, while the likelihood of survival of escaped Baltic herring was questioned as they had lost most of their scales and were in a torpid state when taken onboard the vessel (Vinogradov 1960).

Using a manned towed submersible, Zaferman and Serebrov (1989) observed that dead cod, and more often, dead haddock were found on the seabed in the trawl path. Mortality was believed to be the result of injuries caused by the mesh selection process. However, it can not be ruled out that the dead fish had been discarded or that the mortality was caused by contact with the ground gear. To quantify escape mortality, the fish need to be captured and kept in captivity. To study how mortality progresses over time, the sea-cages are usually monitored by divers and dead fish removed regularly (Main and Sangster 1990; Sangster et al. 1996; Soldal and Engås 1997; Wileman et al. 1999; Suuronen et al. 2005).

To collect escaped fish, Main and Sangster (1990) used divers to transfer them in plastic bags into cages for survival assessment. They reported high escape mortality of haddock. As catching escapees by hand involves handling, and as a representative sample is difficult to obtain, Main and Sangster (1990) improved the sampling technique. They collected the fish by enclosing the codend with a cover that was subsequently released from the trawl and towed to sea-cages for survival assessment. Lower mortality estimates were then obtained for haddock and such covers have been used in subsequent field studies (Soldal et al. 1991; Sangster et al. 1996; Suuronen et al. 1996a,b, 2005; Soldal et al. 1993; Lehtonen et al. 1998; Wileman et al. 1999). The covers have later been shown to reduce the water flow around the codend, which can bias escape and mortality rates (Breen et al. 2002). The covers may also block the codend meshes if they lie close up to the meshes, thus affecting escape rate and survival (Suuronen et al. 1996a). The sampling time, i.e. the time that fish spends in the cover/cage assembly during trawling, has been shown to have a negative effect on survival (Wileman et al. 1999; Breen et al. 2002). At commercial towing speeds, the relative speed of water inside the cover has been observed to be so high that smaller fish could not sustain the swimming speeds required to stay ahead of the rear part of the cover/cage (Breen et al. 2002). The sampling time ought therefore to be short and controlled (Lehtonen et al. 1998; Wileman et al. 1999).

The cover containing the escapees may be transferred to seabed cages after it has been released from the trawl (Sangster et al. 1996; Suuronen et al. 1996b; Wileman et al. 1999). To reduce the risk of mortality due to experimentally induced exhaustion and stress when transferring the fish to the cage sites, Sangster et al. (1996) developed an underwater container to keep the fish in a flow-free environment during the transfer.

Escapees have also been collected by using large cages attached directly to the cover during sampling (Soldal et al. 1993; Jacobsen 1994; Soldal and Engås 1997; Suuronen et al. 2005). After releasing the cages from the cover they have either been sited and anchored on the seabed (Soldal et al. 1993; Lehtonen et al. 1998; Suuronen et al. 2005) or suspended in the water column (Jacobsen 1994; Soldal and Engås 1997). Whichever method is used, fish transfer and containment must be done in such a manner as to minimize stress and injury to the fish. Changes in depth, and hence hydrostatic pressure, during transfer is suspected to affect fish mortality (Breen 2004). The gas-filled physoclistous (closed) swim bladders of gadoid fish obey Boyle's Law and expand as the ambient pressure falls. Rapid depressurization can cause mortality due to the overinflated swimbladder compressing organs (Keniry et al. 1996), stress due to loss of buoyancy control or possibly barotrauma (Musyl et al. 2003).

### 1.2.3 Previous studies

The mortality of cod and saithe after escaping from codends (Soldal et al. 1993; Jacobsen 1994; Suuronen et al. 2005) and grids (Soldal et al. 1993) has been found to be negligible. Laboratory experiments on survival of cod after mesh penetration (DeAlteris and Reifsteck 1993) and combined exhaustion and intentionally induced injuries (Soldal et al. 1993) support the results from the field experiments. Although mortality in cod and saithe is negligible, haddock have been shown to be more vulnerable, but their observed mortality rates have been highly variable. The mortality estimates ranged from 25 to 83% in the first studies when divers were used but became lower as the methodology was improved (Main and Sangster 1990). Soldal et al. (1993) found 1 – 10% mortality of haddock after grid and mesh selection and Jacobsen (1994) found 15% mesh escape mortality.

Soldal et al. (1993) observed similar rates of mortality of haddock in their experimental groups as in the control group. Fish for the latter group were obtained by removing the codend. The mortality was thus not due to the escape through meshes and grids, as the fish in the control group avoided that process. Moreover, if the mortality resulted from injuries caused by mesh penetration higher rates would be expected in larger fish with larger girths. However, Sangster et al. (1996) and Wileman et al. (1999) found the highest mortalities among small haddock and whiting, and negligible mortality of fish above 25 cm. The same trend has been found in herring (Suuronen et al. 1996a,b). The cause of this length relationship has been suggested to be exhaustion resulting from strenuous swimming when the fish try to maintain their station relative to the trawl (Wileman et al. 1999). Smaller fish have poorer swimming ability than larger individuals (He 1993; Breen et al. 2004), and presumably tire first and drop back towards the codend. Mortality resulting from exhaustion was documented in experiments designed to determine the swimming endurance of haddock (Black 1958; Beamish 1966; Breen et al. 2004). Breen et al. (2004) reported that 40 % of the fish used in their experiment died following exhausting swims. Forced swimming and stress raise levels of blood lactic acid and catecholamines, the net effect being osmotic imbalance resulting in ionic overload from which the fish may never recover (Mazeaud and Mazeaud 1981). The results obtained by Soldal and Engås (1997) support this finding, as they show negligible mortality of haddock from an experiment conducted at lower towing speeds (1.2 knots) compared with other studies at faster speeds (2.5-4 knots) (Soldal et al. 1993; Jacobsen 1994; Sangster et al. 1996; Wileman et al. 1999). The haddock is considered a poorer swimmer than cod and saithe (He and Wardle 1988; Videler and Wardle 1991; Breen et al. 2004), which could, at least partly, explain the species-specific mortality.

Injuries caused by contact with the net, spiny fish or objects in the codend may result in skin damage, which can be substantial for haddock (Sangster and Lehmann 1994; Lowry and Sangster 1996; Breen 2004) and may induce stress. If infections follow or major organs are damaged, the injuries can be fatal.

Any observed mortality generally occurs soon after escape and the majority of the fish that die, do so within the first three days, and mortality has almost ceased after eight days. This 'primary' mortality is probably due to injuries/trauma related to the fishing process, but occasional 'secondary' mortality resulting from infections caused by initial injuries/trauma and/or captivity stress may be observed (Wardle 1981; Lowry and Sangster 1996; Sangster et al. 1996; Breen and Sangster 1997; Wedemeyer 1997; Wileman et al. 1999).

## 1.3 Objectives of the thesis

Attempts to improve size selectivity have the general aim of reducing discard mortality or landings of small fish. Fish that encounter a fishing gear but are not caught should therefore survive to recruit to the exploited stock. Size selection and escape mortality are thus related issues. It is clear that some fish escape beneath the fishing line. If such escapes are size-related, they will also contribute to the overall trawl selectivity. Previous work on size selection, however, have focused on codend and special selectivity devices such as selection grids. The grids have hitherto not been compared directly to codend selectivity. Escape mortality is currently not included in stock assessment models since it is generally unknown. Its inclusion also requires knowledge of selectivity.

In this thesis, I have evaluated:

1. The selectivity of a commercial rockhopper ground gear for cod, haddock and saithe (Paper I), in order to demonstrate its relevance to overall trawl selectivity.

2. The selectivity of a Sort-V sorting grid and codend meshes of 135 and 155 mm mesh sizes for cod (Paper II), in order to determine whether diamond mesh codends and grid-mesh combinations with similar $L_{50}$s produce different selection ranges.

3. The probabilities of survival of cod, haddock and saithe escaping through sorting grids and codend meshes in the Barents Sea trawl fisheries (Paper III; Paper IV).

# 2 Abstracts of papers

### Paper I

#### Ólafur Arnar Ingólfsson and Terje Jørgensen

Escapement of gadoid fish beneath a commercial bottom trawl: relevance to the overall trawl selectivity. *Fisheries Research*, in press

Escapement of Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*) beneath a commercial bottom trawl, rigged with a 60 cm diameter rockhopper gear, was studied in the Barents Sea. The study was performed off the coast of north Norway in March/April 2003. In order to collect the escapees, three sampling bags were attached behind the rockhopper gear. Approximately one third of the cod and a quarter of the haddock available to the trawl escaped. Cod escape rates were highly length dependent, following a sigmoid curve with an estimated length at 50% escape of 38.5 cm and interquartile width of 34.1 cm. Length dependence was less pronounced in haddock. The escape rate of saithe was not length dependent, and on average seven percent passed under the trawl's fishing line. Fish abundance had no observable effects on escape rates. Both video observations and scale abrasions on the fish caught in the collecting bags showed that some of the escaped fish had been overrun by the gear.

### Paper II

#### Terje Jørgensen, Ólafur Arnar Ingólfsson, Norman Graham and Bjørnar Isaksen

Size selection of cod by rigid grids; is anything gained compared to diamond mesh codends only? *Fisheries Research*, in press

Size selective grids were introduced into the Barents Sea demersal trawl fishery in 1997. It was believed at the time that in comparison to standard diamond mesh codends, grids had better selective properties, i.e. narrower selection range. Few studies have directly compared the selective properties of the combined grid and codend with that of the codend only. In this study we describe two experiments carried out in 2002 and 2003, where we directly compared the properties of codend selectivity for cod (*Gadus morhua*) with the combined selectivity of a Sort-V grid and a codend. In 2002 we used small-meshed covers, whereas the twin trawl method was used in 2003. In both experiments we compared the selectivity of a 135 mm codend only with that of a trawl fitted with a 135 mm codend and a 55 mm grid, which is the mandatory configuration. In 2003 we also estimated the selectivity of a 155 mm diamond mesh codend, having an $L_{50}$ similar to that of the grid and 135 mm codend combination. The results presented no evidence that the grid and mesh combination had sharper size selection than codend meshes. The introduction of the mandatory use of grid in the fishery in 1997 therefore only increased $L_{50}$, and corresponded to a mesh size increase of around 20 mm. Mean selection length of the grid was inversely related to catch rates in the 2002 experiment when large catches were taken. Grid selection appeared less affected by seasonal variations in degree of stomach fullness or condition than mesh selectivity. Other situations where grid selection might perform better than mesh selection are discussed.

### Paper III

**Ólafur Arnar Ingólfsson, Aud Vold Soldal and Irene Huse**

Survival and injuries of cod, haddock and saithe that escape through codends and sorting grids in a commercial fishery

Survival rates and injuries of haddock (*Melanogrammus aeglefinus*), cod (*Gadus morhua*) and saithe (*Pollachius virens*) were studied after they escaped from codends and grids in full-scale trials in the Barents Sea. Escaped fish were collected in a cage connected to a hooped codend cover for the codend escapees, or a grid cover for the grid escapees. Trawl-caught controls were sampled by removing the codend and attaching the cage to the trawl extension. Acoustic release devices were used to time the sampling. Due to technical problems, the replicates were fewer than planned. Control fish were also sampled in fish traps. Survival rates of cod and saithe were 100%. Haddock survival was lower (50–98%) and in some cases related to fish length. Haddock survival could not be shown to depend upon the selectivity device, but the number of replicates does not allow us to draw a firm conclusion. Scale loss of haddock decreased as fish length increased in all experimental groups. Cod and saithe suffered fewer skin and fin injuries than haddock.

### Paper IV

**Ólafur Arnar Ingólfsson, Aud Vold Soldal, Irene Huse and Mike Breen**

Escape mortality of cod, saithe and haddock in a Barents Sea trawl fishery

Experiments are described to investigate the survival of gadoid fish in the Barents Sea escaping from a demersal trawl, with and without a sorting grid, at high and low levels of fishing intensity. The mortality for cod (*Gadus morhua*) and saithe (*Pollachius virens*) was negligible and unrelated to the experimental parameters: selection device (codend meshes and sorting grid) or fishing intensity. Haddock (*Melanogrammus aeglefinus*) mortality was generally higher, more variable and inversely related to fish length, and was neither related to selection device nor fishing intensity. The mortality of haddock escaping through the selective devices in the trawl was not significantly different from that of the control group, which avoided passing through either the codend meshes or selection grid, suggesting that the escape per se is not the main cause of mortality. It is concluded that the observed mortality of haddock is confounded by methodological problems, in particular instability of the observation cages, and does not reflect the true escape mortality.

# 3 Discussion

## 3.1 Selectivity

This thesis deals with the selection of cod, haddock and saithe beneath a commercial trawl rigged with rockhopper gear in the Barents Sea fisheries (Paper I), as well as mesh and grid selectivity for cod conducted with both the twin trawl and the covered codend method (Paper II).

### 3.1.1 Ground gear

Escapes of cod beneath the trawl were length-dependent and the retention rate increased with fish length. The retention was described by a logistic curve, with an $L_{50}$ of 38.5 cm and $SR$ of 34.1 cm. The length dependence of haddock escapes was less pronounced, with three out of eight hauls showing a significant length relationship. On average, 23% of haddock passed beneath the trawl's fishing line. Seven percent of saithe escaped beneath the trawl, showing no sign of length-dependent escape.

In order to estimate the degree of selectivity in the trawl mouth, i.e. escape underneath the ground gear, we used sampling bags that could be described as small-meshed trawls rigged behind the ground gear of the main trawl to collect the escapees (Paper I). The bags were similar to those used by Engås and Godø (1989b), with some modifications. The ground gears of the trawls were of different dimensions, and side panels were therefore inserted in the collecting bags in order to increase the vertical opening. Moreover, the ground gear of the bags in our study consisted of 10 cm rubber discs, compared to 20 cm in the study of Engås and Godø (1989b), in order to reduce the risk of losing fish underneath the bags. Unfortunately, this probably caused the gear to catch on more stones, causing frequent damage to the nets.

In order to obtain an estimate of ground gear selectivity we need to catch all the fish that enter the trawl and all fish that escape underneath it. Both the bags and the trawl therefore need to be small-meshed. The ground gear of the bags needs to be of small dimensions and was 'chained' down to ensure constant contact with the bottom. The substratum for such experiments therefore needs to be chosen carefully: it has to be representative of commercial fishing grounds but not too rough (to avoid catching stones and damaging the net), and not too soft (to avoid filling them with mud). The twine thickness for the bottom panel should preferably be greater than that used in our experiment (1.8 mm). An alternative could be to use abrasive-resistant mats instead of the netting. The bags should have positive or neutral buoyancy. Otherwise, they may hang vertically during haulback, and as the fish's swim bladders expand due to decreasing ambient pressure, the fish become buoyant and may float out of the front opening. Stones caught by the bags will affect their buoyancy and also damage the net. This caused several hauls to be invalid in our experiment.

The trawl performance during the experiments was assessed to be similar to normal commercial fishing conditions on the basis of measurements of headline height and wing spread. Furthermore, it is unlikely that the bags affected the bottom contact of the ground gear, as the drag of the bags was in the horizontal plane. However, it is possible that some fish may have passed beneath the bags, thus leading to escape rates being underestimated. Since the ground gear of the bags had small dimensions and the bottom was observed to be flat (apart from occasional boulders), the error due to these sources is regarded as negligible.

With 40 rockhopper discs (60 cm diameter) dispersed over a 18.9 m long fishing line, escapes of cod beneath the trawl's fishing line were clearly length-dependent, with an $L_{50}$ of 38.5 and $SR$ of 34.1 cm (Paper I). This length dependence agrees with the results obtained by survey trawling (Engås and Godø 1989b; Walsh 1992; Dahm 2000), and the observed escape rate was similar to that found by Engås and Godø (1989b), in spite of differences in the ground gears used in the studies. They used sparse roller gear (19.7 m fishing line with 15 rubber bobbins of 36 to 46 cm diameter) and obtained an $L_{50}$ of 39.7 and $SR$ of 35.8 cm (calculated from the published data). Hence, the space between the discs/bobbins may not be a determinant of cod escape rate. Walsh (1992) observed a similar $L_{50}$, but a lower $SR$ of approx. 18 cm (calculated from the published data). The different trawl types make direct comparisons infeasible. Walsh (1992) used a large-mesh trawl, and it cannot be ruled out that there has been some undetected selection in the trawl belly. Moreover, his study was performed in shallow waters ($<$100 m), and thus presumably at higher ambient light levels than in Paper I (200-300 m) and Engås and Godø (1989b) (100-300 m).

The marked size-dependent difference in escape rates of cod may be associated with size-related differences in swimming ability (He 1993) or with differences in sensory ability, since visual acuity increases with fish size (Fernald 1988). If differences in vision play a role, larger fish should be able to react to the approaching ground gear at a greater distance than the smaller ones. The selectivity properties of the ground gear might then be altered by the use of contrast colours and/or illumination.

Haddock have been observed to generally stay higher off the bottom than cod (Walsh and Hickey 2003). The lower proportion of haddock available to the ground gear may explain why they show less length dependence in escapes (non-significant in five out of eight hauls) than cod (Paper I). About 23% of the haddock and 7% of the saithe (average) passed beneath the trawl, irrespective of length. Species differences in escapes have also been observed in similar experiments (Engås and Godø 1989b; Walsh 1992). Species-specific behaviour in the trawl opening has been observed by Main and Sangster (1981) and has been utilized to design species-selective trawls by the use of horizontal separator panels (Main and Sangster 1982, 1985; Engås et al. 1989).

The fish that passed beneath the ground gear were often observed to have abrasions across their body (Paper I). Fish have been seen colliding with ground gears (Main and Sangster 1983; Walsh and Hickey 2003). Some of the fish in our study had muscular contusions, penetrating to the spinal bone. It is possible that some degree of mortality followed.

There is uncertainty as to whether artificial light affects fish behaviour in the trawl opening, and thus undermines the validity of behavioural observations using cameras and light. Weinberg and Munro (1999) found no effect of light in five species, among them Pacific cod (*Gadus macrocephalus*). In Paper I, however, it is suggested that artificial light may affect the capture efficiency of the trawl, as the results of the single retention curve for cod obtained when light was used deviated markedly from those of eight hauls without light. These two observations are not necessarily conflicting, as Weinberg and Munro (1999) did their work in shallower water on different species. The lights in the two experiments were also positioned differently.

### 3.1.2 Mesh and grid

The $L_{50}$ and $SR$ of a traditional diamond mesh codend with 155 mm mesh size were 55.4 and 14.0 cm, respectively, and not significantly different from those of a combination of grid and 135 mm codend ($L_{50}$ of 53.4 and $SR$ of 11.7 cm) (Paper II).

The effects of catch and catch rate on both mesh and grid selectivity have been addressed in several studies. The $L_{50}$ for the grid-mesh combination has been found to decrease with catch rate for both the Sort-V and Sort-X grids (Anon 1998; Kvamme and Isaksen 2004; Paper II), suggesting that the grids have capacity problems at high catch rates. Several studies have verified an increase in $L_{50}$ for codends with an increase in catch size (Dahm et al. 2002; O'Neill and Kynoch 1996; Graham et al. 2004; Kvamme and Isaksen 2004). Neither catch nor catch-rate effects were found for the codend selection in Paper II, with median catches of 3.7 tonnes and quantiles of 2.3 and 5.3 tonnes. At the beginning of a tow, while the catches accumulate in the codend, selectivity may improve as the meshes open, up to a point where the maximum diameter of the codend is reached. Selection is likely to stabilize when that point is reached (O'Neill and Kynoch 1996).

To fulfil the criterion of minimising catches of undersized fish while retaining fish above minimum legal size, a selectivity device with narrow $SR$ is preferable. No significant difference in selectivity for cod was observed between the 155 mm PA codend and a combination of Sort-V grid with 55 mm bar space and 135 mm mesh size (Paper II). This conclusion is supported by results from comparative studies, in which no difference in $SR$ was identified between a 135 mm codend and grid-mesh combination with 55 mm bar spaces and 135 mm codend (Kvamme and Isaksen 2004; Paper II). The selectivity properties of the Sort-V grid could not be shown to be different from that of the Sort-X grid for cod (Isaksen et al. 1998a,b). Therefore, the hypothesis that traditional diamond-mesh codends with 155 mm mesh size give equivalent $SR$ as does grid-mesh combination with 55 mm bar-spacing and 135 mm mesh size cannot be rejected (but see later; Power analysis).

The $L_{50}$ and $SR$ for haddock have been estimated at 47.7 and 9.6 cm respectively for the Sort-X grid (Eduardo Grimaldo, Norwegian College of Fishery Science, pers. comm., data from January 2004). Using a 140 mm mesh codend, Huse et al. (2000) found $L_{50}$ and $SR$ for haddock of 56.6 and 10.1 cm respectively (data from February 1996). Although we need to be careful when comparing results across surveys, these results indicate that SRs for grid and mesh are also similar for haddock.

Size selectivity can be expected to vary with fish girth, which in turn varies with condition and season (Wileman et al. 1996). It has also been suggested that seasonal variations (temperature and/or fish condition) affect $L_{50}$ of diamond meshed codends more than can be explained by changes in girth alone (Tschernij et al. 1996; Özbilgin et al. 1996). In the selectivity experiments in 2002, the cod were feeding on capelin and had expanded abdominal cavities and thus larger girths than in 2003 (Paper II). The $L_{50}$ for 135 mm codend in the 2002 experiment was lower than in 2003 (Paper II) and the one by Kvamme and Isaksen (2004). The increased fish girth due to intensive feeding was thus suggested as having affected the $L_{50}$ of the codend in 2002. The $L_{50}$ for the grid was similar in both years. This difference cannot therefore be explained by the difference in the applied methods alone (covered codend in 2002 and twin trawl in 2003). A possible explanation is that the grid selectivity is less affected by stomach contents. Grid penetration is determined by the inter-bar distance in relation to the maximum width of the fish. The belly is to some extent laterally compressible, and the grid slots allow for ample space dorsally and ventrally, unlike meshes, which have a fixed circumference.

The selectivity properties of the grids can be altered, for example by adjusting the grid angle and blocking the grids, but changing the selectivity properties of the grids would currently be illegal, since their constructions and rigging are strictly specified by regulations. The selectivity properties of the codend can be affected by e.g. changing the codend circumference, extension length (Reeves et al. 1992) or twine thickness (Lowry and Robertson 1996). These factors are not defined in the regulations for the Norwegian Economic Zone in the Barents Sea. If the use of grids were to be abolished, these factors would have to be considered.

### 3.1.3 Power analysis

The estimates obtained with the twin trawl method as used in the experiments described in Paper II are associated with higher degree of variability than those of the covered codend method (Wileman et al. 1996; Madsen and Holst 2002). The effect of this is in fact seen in the paper, and a larger number of hauls should have been carried out to compensate for this uncertainty. The fact that we could not detect a difference between the $SR$ for 155 mm codend and a combination of grid with 55 mm bar space and a 135 mm codend does not necessarily mean that there is none, and we must consider whether our experimental setup allows us to conclude that there is no difference.

We determine the model with two parameters; $a$ and $b$. The $SR$ is then $log(9)/b$; we can thus test hypotheses about the $SR$ by working on the slope parameter $b$. The number of samples we need to test our hypothesis,

$$H_0 : b_{Mesh} \geq b_{Grid} \qquad vs. \qquad H_1 : b_{Mesh} < b_{Grid}$$

depends on the variance of $b$, the size of the difference ($\Delta b$) that we want to be able to detect as significant, the risk of a Type I error ($\alpha$=0.05) and the risk of Type II error ($\beta$=0.2).

Based on the data from the twin trawl experiments in 2003, we obtained $SR$=14.0 cm ($\hat{b}_{Mesh}$=0.157) for 10 hauls with 155 mm mesh size and $SR$=11.7 cm ($\hat{b}_{Grid}$=0.188) for seven hauls with a combination of grid and 135 mm mesh size, i.e. a 2.3 cm insignificant difference in $SR$ ($\Delta\hat{b}$=0.031). A power analysis tells us how big a difference we are able to detect with this method with the number of replicates used, and how many hauls we need to detect this observed difference.

The model parameter estimate $b_{ij}$ for the $i$-th haul with fixed effects $j$ (mesh and grid) is influenced by within-haul and random (between-haul) variances (Fryer 1991) i.e.:

$$b_{ij} = \hat{b}_j + \varepsilon_{W_{ij}} + \varepsilon_{B_j}$$

where $\hat{b}_j$ is our joint estimate from the $i$ hauls within category $j$, and the within- and between-haul variances are $\varepsilon_{W_{ij}} \sim N(0, R_{ij})$ and $\varepsilon_{B_j} \sim N(0, D_j)$, respectively.

$R_{ij}$ is the vector of within-haul variances for $b_{ij}$, and $D_j$ the between-haul variance. The power of the test can be approximated by a mixture of simulations and bootstrapping (Rob Fryer, pers. comm.). The between-haul error we obtain by sampling from a simulated $N(0, D_j)$ distribution, and the within-haul error we get from simulating $N(0, R_{ij})$ by sampling out of our sample of $R_{ij}$ with replacement. We then do this for the seven grid and the 10 mesh hauls and perform a one-sided t-test with $\alpha = 0.05$. This is repeated 10 000 times and the number of times with a significant difference is recorded. The rate of successes is the calculated test power. For our seven grid hauls and 10 mesh hauls, we get a power of 0.26. In order to fulfil the criteria of power=0.8, the number of paired hauls needed to detect the observed $\Delta\hat{b}$ (Figure 3A) has to be increased to 40. Furthermore, with an experimental setup comprising 10 paired twin trawl hauls and our observed variation, we are not capable of detecting a smaller $\Delta\hat{b}$ than 0.067 (Figure3B).

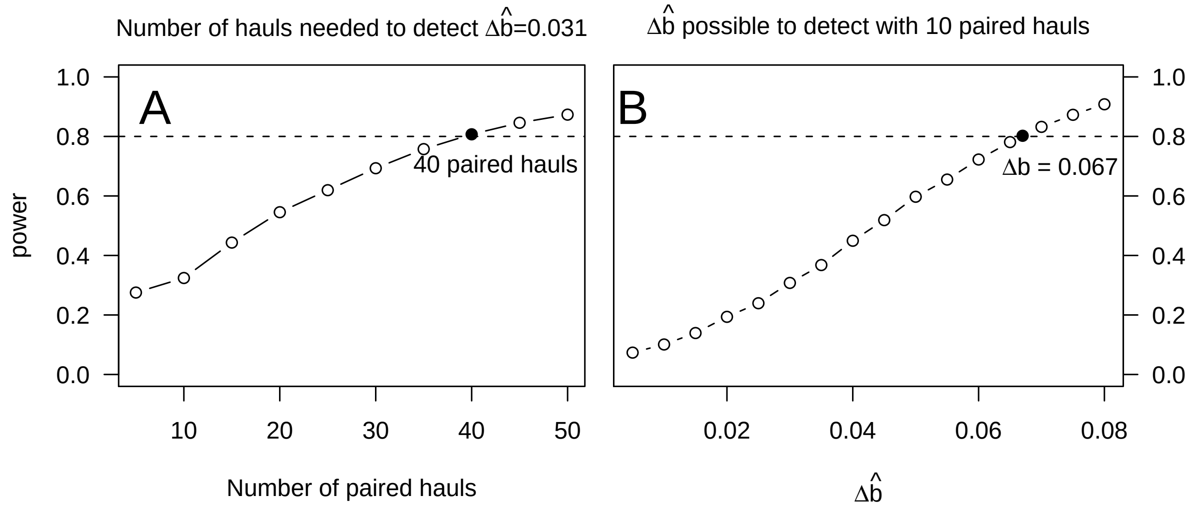


Figure 3: Power analysis. A: Number of twin trawl hauls needed to detect $\Delta\hat{b}$ =0.031. B: $\Delta\hat{b}$ that can be detected with 10 paired selection hauls using the twin trawl method. Based on data from Paper II.

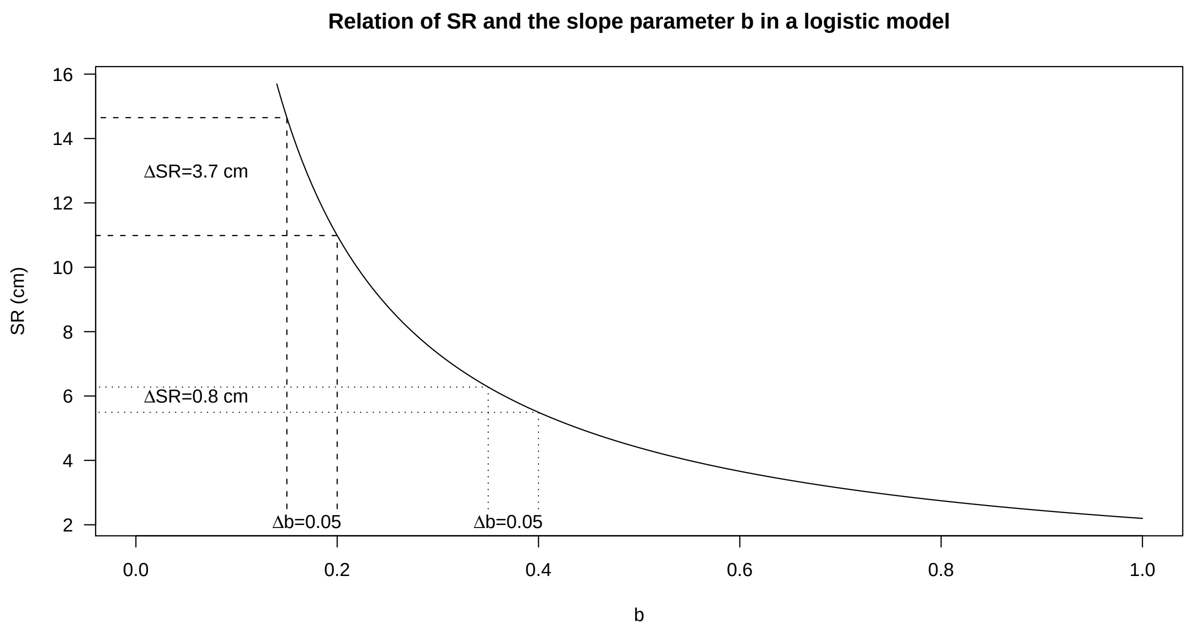


Figure 4: Relation of $SR$ and the slope parameter $b$ in a logistic model. $\Delta SR$ for low values of $b$ are larger than for high values of $b$ for the same $\Delta b$.

Assuming that the variances are constant over a wide range of $b$s, a given $\Delta SR$ for wide $SR$s will be more difficult to detect than for narrow ones, since $SR$ is inversely related to the parameter $b$ (Figure 4).

An experiment must have clear objectives, and it should be realized in advance whether the available research methods are capable of meeting these objectives. A difference in $SR$ of $\leq 4$ cm between two selectivity devices, both having $SR$ of 10-15 cm may thus be difficult to detect with the twin trawl method when the number of replicates is around 10 hauls. For this reason, performing an experiment to determine a difference in $SR$'s for two devices with only a small number of hauls using the twin trawl method should not be done. A larger number of replicates will be needed, or the covered codend method could be used as it results in less variance.

### 3.1.4 Total selection

Previous studies have focused only on the selectivity of the codend or special selectivity devices. As shown here, the overall selection of the trawl is a more complex product of the various selection processes. Considering a bottom trawl in the Barents Sea with a rockhopper gear, selection grid and a 135 mm codend, and thus three selection processes (assuming selection through the trawl belly to be negligible), the overall selection curve $r_{tot}(l)$ of the trawl becomes a product of the processes $r_i(l)$, that is:

$$r_{tot}(l) = \prod_{i=1}^{n} r_i(l) \qquad n = 3$$

Where $n$ is the number of selection processes. Using the estimates from Papers I and II (2002 data), the $L_{50}$ and $SR$ for the rockhopper were 38.5 and 34.1, grid 55.2 and 11.5 and codend 41.8 and 8.4 cm, respectively. We then get a resulting asymmetric selection curve $r_{tot}(l)$, with an $L_{50}$ and $SR$ of 58.3 and 13.4 cm, respectively (Figure 5).

As Figure 5 shows, post-selection in the codend has negligible effects on the combined grid and mesh selection, and only a small effect on the smallest length classes is noticeable. In Paper II, however, these two selection processes were calculated as one, because the product curve gave a worse fit. As the grid selection has the highest $L_{50}$, it becomes the dominant factor. The relatively flat retention curve for the rockhopper gear has some impact, increasing the total selection by about 3 cm and the $SR$ by about 2 cm. It also contributes to less retention of larger fish.

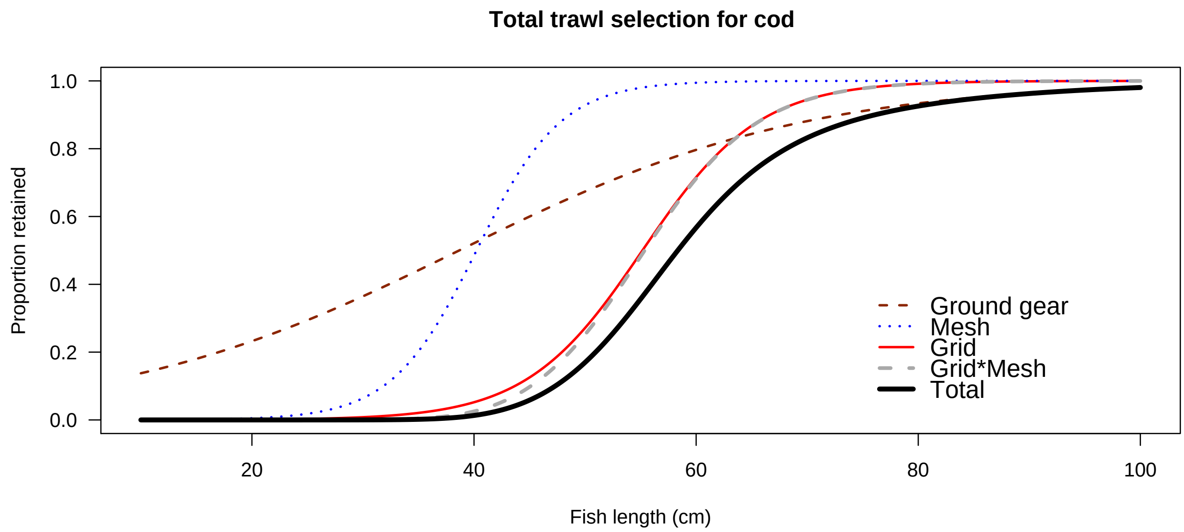


Figure 5: The different selection processes in the trawl and the resulting total selection.

## 3.2 Escape mortality

This thesis covers four experiments on mesh and grid escape mortality presented in two papers. Experiments performed in 2000 and 2001 are presented in Paper III, while Paper IV reports on experiments in 2004 and 2005. Cod and saithe mortalities were investigated, but the discussion focuses on mortality of haddock, as this proved to be a vulnerable species.

### 3.2.1 Methodological considerations

Data from each year were analysed separately, and the between-cage mortality in Paper IV was modelled as random effects. The data from 2000 (Paper III) differ from the others in that they show less pronounced size-related mortality. There were variations in mortality between trials as well as cages. The between-trial variation can at least partly be explained by changes in experimental methods. The variation is modeled as random effects by using a Generalized Linear Mixed Model (Venables and Ripley 2002; Paper IV). By setting year as a factor, the mortality in year 2004 (Paper IV) appears to be less than in 2001 (Paper III). The difference was not significant ($p>0.05$), but when a badly closed cage in the 2001 experiment was excluded from the analyses, data yielded significance.

In these experiments the methodology was not static, but was developed and adapted as problems were identified in the course of the trials. In 2000, cylindrical collapsible cages were used, similar to the ones used by Soldal and Engås (1997) and Jacobsen (1994). In 2000, the pre-set depth limit for trawling was 100 m and the cages were attached to a buoy at the surface by a 50 m rope. This was done in accordance to the criteria for maximum pressure reduction of 50% suggested by Tytler and Blaxter (1973). Rapid depressurization can cause mortality due to overinflated swimbladder compressing organs (Keniry et al.

1996), stress due to loss of buoyancy control or possibly barotrauma (Musyl et al. 2003). The cage with the highest mortality was accidentally released at depths greater than the pre-set depth limit. Moreover, due to strong currents in the experimental area the cages drifted and it is possible that their depth below the surface was less than the planned 50 m. More rigid cage constructions were used the following year.

In both 2000 and 2001 there were problems with the cage closing, causing some cages to be considered invalid. In the following trial in 2004 (Paper IV), the cages were closed by means of a rigid door, which was kept open during shooting and closed when sampling began. This system proved to be reliable. It was also observed that the drag of the heavy cage construction caused the tapered extension in front of the codend to be tight, narrow and inhibitory for fish passage during trawling. To remove the strain on the extension, the cover was attached to the belly section in front of the extension instead of attaching it to the rear end of the extension.

In 2001 the cages were towed along the bottom over a short distance to a sheltered site at 20-30 m depth. We could not rule out that the observed size-related haddock mortality was caused, at least partly, by the towing of the cages to the sites. It has been suggested that exposure to continuous flow of water in the cages during sampling may affect survival (Breen et al. 1998). In order to prevent the fish from being pressed to the rear part of the cages, water flow within the cages was reduced by lining the rear part. This was done in accordance with experiments conducted by the Fisheries Research Service, Marine Laboratory (unpublished results). It was also decided to leave the cages at the site where they were released, as further towing of the cages might induce stress on the fish and thus affect mortality.

Haddock mortality was more pronounced in cages at greater depths (Paper IV, Figure 5). When cage deployment was followed by a strong current speed (tidal range measured), mortality increased further (Figure 6). The tidal currents in the area were observed to be strong (exceeding 0.6 $ms^{-1}$) when measured in 2005. This interaction between anchoring depth and current speed probably affected the stability of the observation cages. The cages were connected with a cable of fixed length to a surface buoy. The angle between the cable and vertical (depth) thus reduces with increasing depth. Lifting forces on the cages due to horizontal water movements at bottom or surface will be inversely relate to that angle and thus directly related to depth. Movements of the cages could have induced stress, resulting in increased mortality.

As the cages were suspected to move with the currents and rise vertically, depth loggers were attached to each cage in the last trial in 2005 (Paper IV). At the beginning of this experiment, some cages hit the bottom and broke. Floats were therefore added to increase buoyancy. The depth loggers showed, however, that some cages did move vertically and even rose to the surface on days with strong winds/currents. The mortality in year 2005 (Paper IV) was significantly higher than in 2001 ($p<0.05$) and 2004 ($p<0.001$), probably

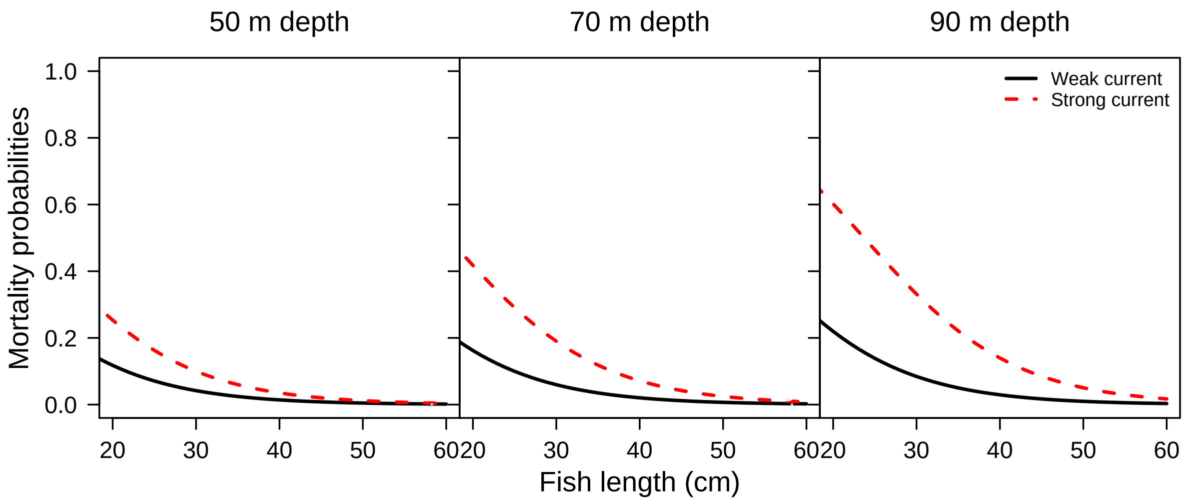


Figure 6: Predicted haddock mortality as a function of anchoring depth and current speed.

at least partly as a result of the instability of the cages.

In summary, the improvements made before the trial in 2004 reduced the experimental mortality of haddock below that of the trial in 2001. However, the combination of strong currents, cage buoyancy, anchoring method and anchoring depth introduced confounding effects on these mortality rates, especially in 2005.

### 3.2.2 Mortality estimates

The mortality observed in mesh- and grid-selected cod and saithe was nil in the experiments in 2000 and 2001 (Paper III), and $\leq 1\%$ in the 2004 and 2005 trials (Paper IV). The low mortality agrees with observations from earlier experiments with these species (Soldal et al. 1993; DeAlteris and Reifsteck 1993; Suuronen et al. 2005). Size selection of these species is therefore a useful conservation measure in terms of reducing discard mortality.

Haddock mortality was higher than that of cod and saithe and ranged from 1 to 80% in the 37 cages during the four trials. Escape mortality was not shown to differ between type of selectivity device (mesh and grid). Nor could any difference be detected between the experimental categories and the controls where no mesh or grid penetration occurred. The actual escape through the meshes and the bars of the grids thus does not appear to induce any discernible mortality. However, it is possible that other effects and the observed variation in mortality estimates mask any effect of fishing intensity or route of escape.

Haddock mortality was generally inversely related to fish length (Papers III and IV). This length relationship is consistent with previously published studies (Sangster et al. 1996; Breen and Sangster 1997; Wileman et al. 1999), and may result from fatigue when fish try to maintain their position relative to the moving trawl (Wardle 1993). When towing speed exceeds the swimming capabilities of the fish they may display symptoms of stress (Olla et al. 1997). The swimming performance of haddock improves with fish length (He 1993; Breen et al. 2004) and smaller fish therefore tire first. Exhaustion can be fatal due to elevated levels of lactic acid in the blood, causing osmotic imbalance (Beamish 1966; Breen 2004). Forty percent of haddock used in a swimming endurance experiment died from exhaustion stress (Breen et al. 2004). The only published study showing negligible escape mortality of haddock (Soldal and Engås 1997) was performed at a lower towing speed (1.2 knots) than in other studies (2.5 – 4 knots), and thus supports this explanation. Haddock is regarded as poorer swimmer than cod and saithe (He and Wardle 1988; Videler and Wardle 1991; Breen et al. 2004) which may explain the between-species difference. In addition, symptoms of stress to the same stressor may be different in different species (Olla et al. 1997).

High and low fishing intensities were compared by starting the experiments in an area closed to trawling, which was later opened to intensive trawling (Paper IV). The high fishing-intensity level was based on commercial effort statistics and was therefore representative of the Barents Sea trawl fisheries. Mortality could not be shown to be affected by increasing fishing intensity. In experiments run simultaneously in the high-intensity area, repeated encounters of cod tagged with electronic tags through trawls were demonstrated (IMR, unpublished). Of 1 000 tagged cod in 2004, 104 were recorded as having passed through the trawls. About one fourth of the cod recorded passed through the trawls more than once during the week-long experimental period. Although these results were based on registrations of cod it is reasonable to assume that repeated encounters of haddock also occurred.

Our studies did not include light level as a potential factor affecting mortality. However, this is a highly relevant consideration, as the ordered pattern of reaction and active swimming due to optomotor response is disrupted in dark conditions (Walsh and Hickey 2003; Olla et al. 2000). The Barents Sea trawl fisheries continue both day and night, mostly at depths greater than 200 m. Under dark conditions, therefore, fish will not become as exhausted due to attempts to keep up with the trawl, but the frequency of collisions with the net may increase (Olla et al. 1997). The overall effect of light level on escape mortality is still a matter for speculation, and needs further study.

If the sampling and caging of escapees raises the level of stress , it may produce mortality in individuals even though they were viable after the escape itself. Confinement is known to cause stress (Pankhurst and Sharples 1992), and if there are also dense concentrations of fish and the cages also include predators but no refuge, the stress response of the fish may ultimately be deleterious (Pickering 1981). However, the numbers of fish in the 19 cages in 2004 (ranging from 35 to 2354) and the presence of potential predators (large cod, saithe and wolffish (*Anarhichas lupus*)) was not found to influence haddock mortality (Paper IV). Due to other methodological problems, however, the resulting mortality was higher than can be explained by the escape following a capture process.

Trawling can entail escape mortalities that cannot be detected in studies of this sort. Physical injuries and capture-related stress may produce changes in fish condition and delayed mortality (Davis 2005). It has also been shown that stress may result in behaviour impairment and reduced ability of the fish to avoid predators (Ryer 2004; Ryer et al. 2004). Escaping fish could also be a source of food for large predators such as sharks and marine mammals. It has been documented that dolphins (Broadhurst 1998) and seals (Marine Research Institute in Iceland, unpublished video observations) follow trawl codends and feed on escaping fish. Evaluating the contribution of these factors to the overall escape mortality would be difficult.

### 3.2.3 Skin injuries

Like mortality, the prevalence of scale loss was inversely related to length for haddock, irrespective of treatment (Paper III). The prevalence of skin injuries was not highest at greatest girth, as would be expected if the penetration process generated the injuries, but increased towards the tail of the fish. These findings are in agreement with previous studies (Soldal et al. 1993; Breen and Sangster 1997). The injuries were thus presumably caused when the exhausted fish collided with the net and beat their tail during their passage through the trawl. Another possible explanation is that exhausted fish rested against the rear wall of the net in the cage during sampling. Cod injuries were less than those of haddock, but showed the same trend in length dependence. There are two likely explanations: The swimming performance of cod is better than that of a haddock of equal size (Videler and Wardle 1991; Breen et al. 2004) and they therefore are more likely to avoid collisions. Cod have also been shown to be more resistant to scale loss and skin injuries (Soldal et al. 1993).

### 3.2.4 Escape mortality at stock level

Escape mortalities of cod and saithe are negligible and need no further consideration here. To be able to assess the effect of escape mortality on the haddock stock, we need to take into account the proportion of the stock that comes in contact with trawl gear and retention probabilities. The proportional escape mortality as a function of length, $m(l)$ can be described as:

$$m(l) = q(l) \times (1 - r(l)) \times f(l)$$

where $q(l)$ is the annual proportion of the stock that comes into contact with trawl gear, $r(l)$ is the retention curve and $f(l)$ is the escape mortality. Selection and mortality data can be obtained from field experiments, while data on the proportion of stock contacting the trawl gear are not readily available. A 'guestimate' can be obtained by using fishing mortality ($F_c$) for large fish, which have a 100% retention probability, assuming that $F_c$

reflects fishing gear contacts per year also for younger year classes, and multiplying by the proportion of catches taken by the trawler fleet.

The $L_{50}$ and $SR$ for haddock grid selection of 47.7 cm and 9.6 cm, respectively (Eduardo Grimaldo, Norwegian College of Fishery Science, pers. comm.) result from the logistic function (Figure 7A):

$$r(l) = \frac{exp(-10.92 + 0.229l)}{1 + exp(-10.92 + 0.229l)}$$

An estimate of mortality rates can be obtained from Paper IV. The confounding effects of anchoring depth and currents are taken into account in the model, and for our prediction we take these effects into account by using the lowest observed values; 47 m depth and 1.29 m tidal difference (Figure 7B):

$$f(l) = 1 - \frac{exp(0.717 + 0.112l - 0.019 \times 47 \times 1.29)}{1 + exp(0.717 + 0.112l - 0.019 \times 47 \times 1.29)}$$

Retention of eight-year-old and older haddock can be assumed to be 100%, and the average fishing mortality for these age-classes in 2002-2004 has been estimated to about 0.4 (ICES 2005a). The natural mortality is set to 0.2, and thus $F_c$=0.4 corresponds to 30% removal of those age classes by fishing gear each year. In this example it is assumed that 70% of haddock catches in the Barents Sea are taken in trawls (ICES 2005a), resulting in an estimated $0.3 \times 0.7 \times 100 = 21\%$ annual trawl contact rate.

The resulting estimated annual escape mortality at stock level, $m(f)$ is about 3% ($F_e$=0.03) for 20 cm haddock and declines with length to 1% ($F_e$=0.01) and 0.3% ($F_e$=0.003) for 30 and 40 cm haddock respectively (Figure 7C). The fishing mortality ($F_c$) for two-year-old haddock (20 cm) in 2002-2004 was estimated to be negligible. The $M$ value for two-year-old haddock is not given in ICES (2005a), but it can be calculated from the number of three-year-old fish of a cohort. The average number of two-year-old haddock at the beginning of 2002-2004 was ∼500 million. The average natural mortality $M$ was 0.85, indicating a removal of ∼286 million individuals (ICES 2005a). Escape mortality of 0.03 thus corresponds to the removal of 6.5 million 0.1 kg individuals (ICES 2005a) weighing about 650 metric tonnes.

Despite limited data on the escape mortality of fish smaller than 20 cm, the model can be extended for prediction purposes by taking the same approach as before, $F_e$ = 0.07 for 10 cm haddock (1-group). The average number at the beginning of 2002-2004 for 1-group haddock was $3.5 \times 10^9$ individuals. Using the catch equation (Beverton and Holt 1957), the population numbers were projected through the life of a cohort. This approach estimates the removal due to $F_e$ to the beginning of the fifth year to be $11 \times 10^6$ fish, weighing approximately 9 500 tonnes. If the mortality due to $F_e$ could be avoided, the catch increase from that cohort during the next six years (age 5-10 haddock) would be

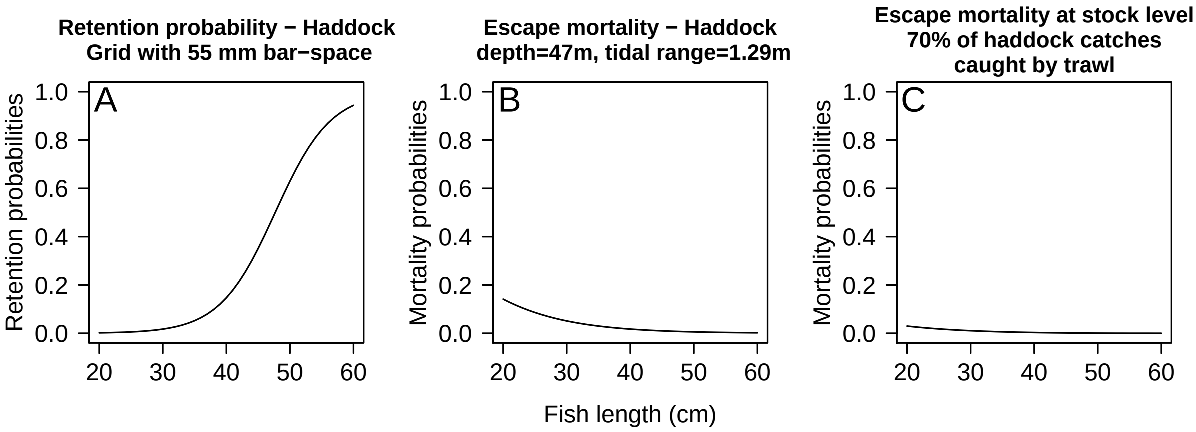


Figure 7: A: Estimates of retention probabilities for haddock. B: Escape mortality of haddock. C: The resulting escape mortality at stock level showing the effects of taking 70% of the haddock catches with a trawl.

about 9 400 tonnes (Table 1). Escape mortality thus appears to have significant effects compared to the annual catches of about 100 000 tonnes from the NEA haddock stock.

Table 1: Estimated catch losses from one cohort resulting from escape mortality. Values of $M$, $F_c$ and catch weight from ICES (2005b). *Weight of age classes 8-10 are based on Russian data from Nov. - Dec. trials the previous year.

| | Age | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Σ |
| M | 2 | 0.85 | 0.38 | 0.25 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | |
| Fc | 0 | 0.001 | 0.025 | 0.15 | 0.295 | 0.505 | 0.44 | 0.456 | 0.318 | 0.472 | |
| Fe | 0.07 | 0.03 | 0.01 | 0.005 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Fish weight (g) | 30 | 100 | 200 | 520 | 870 | 1 230 | 1 660 | 2 250* | 2 600* | 2 600* | |
| Catch loss (t) | | | | | 2 231 | 2 994 | 1 791 | 1 317 | 586 | 483 | 9 402 |

This approximation has certain limitations due to uncertainty in the estimates. Not all fishing gears have a defined 100% retention, size selection that occurs in front of the selection grid is not taken into account and age classes may have different spatial distributions. The estimate of $F_c$ also has the disadvantage of not including unaccounted mortality, e.g. illegal landings. Despite these drawbacks, this exercise serves to offer an approximate value of the level of escape mortality for comparison with estimates of fishing and natural mortality.

## 3.3 Concluding remarks

This thesis has demonstrated the contribution made by the ground gear to the overall selectivity of the trawl. The effects of escape rate beneath the gear should be studied for gears of different weights and dimensions. Some of the escaping fish were struck by the ground gear and the effect of this on mortality should be further investigated.

The effect of introducing the sorting grids was equivalent to an increase in mesh size of about 20 cm. There was no evidence of grids producing narrower selection ranges than traditional diamond mesh codends.

In some studies that have compared two or more selection devices, the number of replicates is low, often less than 10. To compensate for within- and between-haul variances, the number of replicates required to compare the devices needs to be thoroughly evaluated. To avoid carrying out experiments that have little possibility of detecting an existing difference, a power analysis should be performed in advance.

Further comparisons of grid and mesh selectivity should focus on investigating the effects of seasonal variations in temperature and fish condition in order to verify selectivity stability throughout the year. Preferably, two or more fishing areas with fish in similar condition but at different temperatures should be fished. This should then be repeated at different times of the year with fish in various physical conditions. Such experiments need thorough planning, since the temporal and spatial distribution of the fish is not easy to predict.

This thesis has shown that cod and saithe tolerate the selection process well irrespective of selectivity device (mesh/grid) and the intensity level on the fishing grounds. Haddock are more vulnerable, and mortality in this species was shown to be negatively related to length. The results indicate that strenuous swimming to keep up with the moving net may be a primary cause of mortality. The results on survival were confounded to a certain extent by methodological problems, complicating prediction of the actual mortality. Laboratory studies need to be carried out to investigate the effects of combined strenuous swimming and stress on haddock survival. Field studies to improve the sampling techniques should also be performed before additional survival experiments are performed in the field. In particular, the stability of the cages needs to be ensured, and the studies should investigate the effect of varying towing depth, light levels and towing speed.

For any studies of interactions of fish and fishing gear, including selectivity and survival assessment, environmental variables (e.g. ambient light, temperature and current speed), fish condition and catch composition should be recorded and evaluated.

The escape route of cod, saithe and haddock after they have entered the trawl appears not to generate mortality. Hence, as conservation tools, grid and mesh size regulations to prevent catches of undersized fish serve their purpose. Yields from the NEA haddock stock, however, may be reduced due to mortality resulting from exhaustive swimming during the capture process.

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